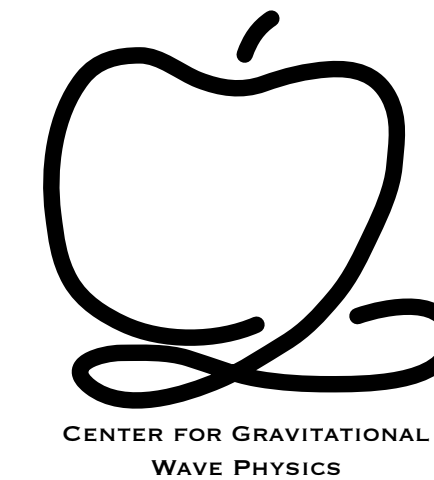# Event Rate for Extreme Mass Ratio Burst Signals in the LISA Band

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During close encounters with a massive black hole (MBH), stellar mass compact objects and low mass main sequence stars on nearly radial orbits will be traveling at relativistic velocities. During the periastron passage these systems will emit gravitational radiation, and depending on the passage timescale, they may be observable by future spaceborne gravitational wave detectors. However, the encounters will only produce bursts in the detector data stream since the orbital frequencies are smaller than the lowest detectable. Here we estimate the event rate for extreme mass ratio bursts (EMRBs) that will be observed by the proposed Laser Interferometer Space Antenna (LISA). Our event rate calculation is based on a static, spherical model for a galactic nucleus scaled to the size and mass of the Milky Way bulge. Using this model, we find an event rate of ~ 15 yr^{-1} in our galaxy with signal-to-noise ratios greater than five. When scaled out to the Virgo Cluster, our model estimates ~ 3 yr^{-1} may be seen from the Virgo.

Inspirals Versus Bursts

The capture and subsequent inspiral of compact objects into MBHs is an anticipated source of gravitational radiation for LISA. These extreme mass ratio inspirals (EMRIs) will produce continuously detectable radiation. However, extreme mass ratio systems can also generate a short burst of radiation, which we classify as EMRBs. EMRBs occur when either the orbital frequency of the bound secondary object is lower than the instrument's sensitivity, or the secondary object is scattered by the central stellar population after a close encounter with the MBH.

The emitted gravitational radiation from an EMRB system causes the orbit to shrink, and thus evolve toward an EMRI phase. However, not all EMRB orbits will necessarily evolve into an EMRI. During a close pericenter pass the secondary object may plunge directly into the MBH, or it may scatter onto an entirely different orbit that may never be captured.

Burst Waveforms

The EMRB orbits are characterized by a wide range of orbital periods ($\sim 10^{-2} - 10^9$ years) and eccentricities close to unity. Secondary objects on these orbits are highly relativistic during periastron passage, with typical velocities an appreciable fraction of the speed of light ($v_{\mathrm{peri}} \sim 0.3c$). The gravitational wave emission from these binaries are short bursts in the time domain, and are thus very broadband, typically covering the entire LISA frequency domain.

Shown below are quadrupole order, canonical waveforms from a white dwarf encountering the Milky Way central MBH.
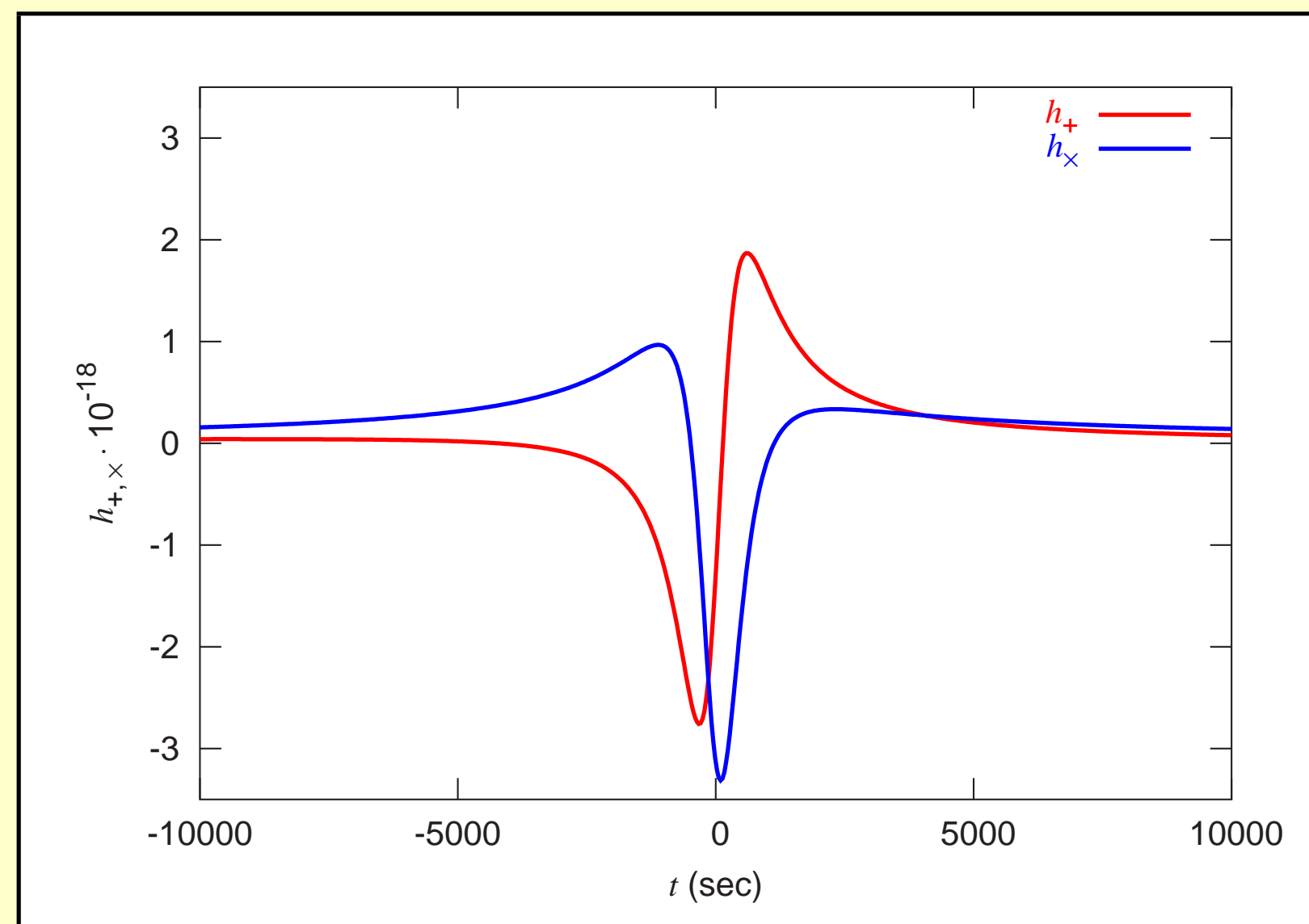
A simplified estimate for the signal-to-noise ratio (SNR) with respect to the LISA mission is

$$SNR \approx 100 \left(\frac{R}{8\,\mathrm{kpc}} \right)^{-1} \left(\frac{M_\star}{\mathrm{M_\odot}} \right) \left(\frac{v_{\mathrm{peri}}}{0.3c} \right)^2 \left(\frac{\Delta t}{10^3\,\mathrm{s}} \right)^{-3/2},$$

where $\Delta t = r_{\mathrm{peri}}/v_{\mathrm{peri}}$ estimates the periastron passage time, R is the distance to the EMRB, and $M_\star$ is the mass of the secondary object. The above scaling implies that detectable SNR values ($\gtrsim 5$) are possible for relativistic orbits.

Stellar Model

In this preliminary investigation, we model the Milky Way bulge as a spherical stellar system with the density profile of an η model, which gives the mass per unit phase space. We set the total size of the model to 2 kpc, the total mass of the stellar component to 2×10^{10} M$_\odot$, and the total mass of the MBH to 4×10^6 M$_\odot$.

We assume that the stellar mass density results from a single burst of star formation 10 Gyr ago, and that the number of stars per unit mass follows a Kroupa IMF. From the IMF we divide our stellar mass into the number of compact objects and low mass main sequence stars on each orbit that survive tidal disruption. Our calculations neglect the effects of mass segregation and multiple episodes of star formation, and assumes the orbits are always occupied.

To isolate the potential EMRB phase space from a larger sampling space, we discard orbits that are either unbound, plunge directly into the MBH, have relaxation times shorter than their orbital periods, or orbits that radiate so strongly their inspiral time is shorter than a dynamical time. We also include only those orbits with periods longer than 10^5 s, otherwise they will be continuous LISA sources. The adjacent plot shows the region of phase space, parameterized by the eccentricity and periastron distance, left after our cuts.
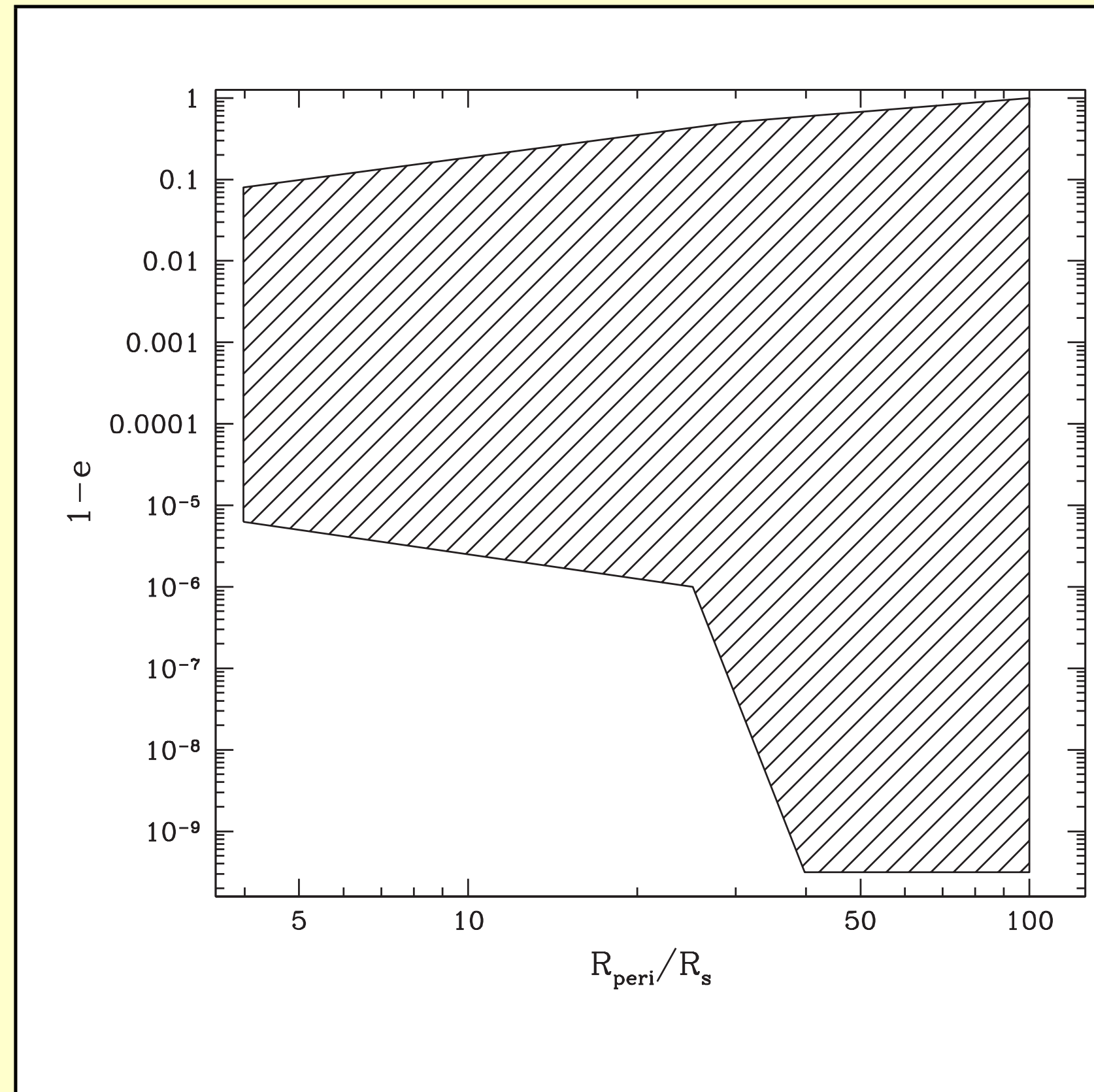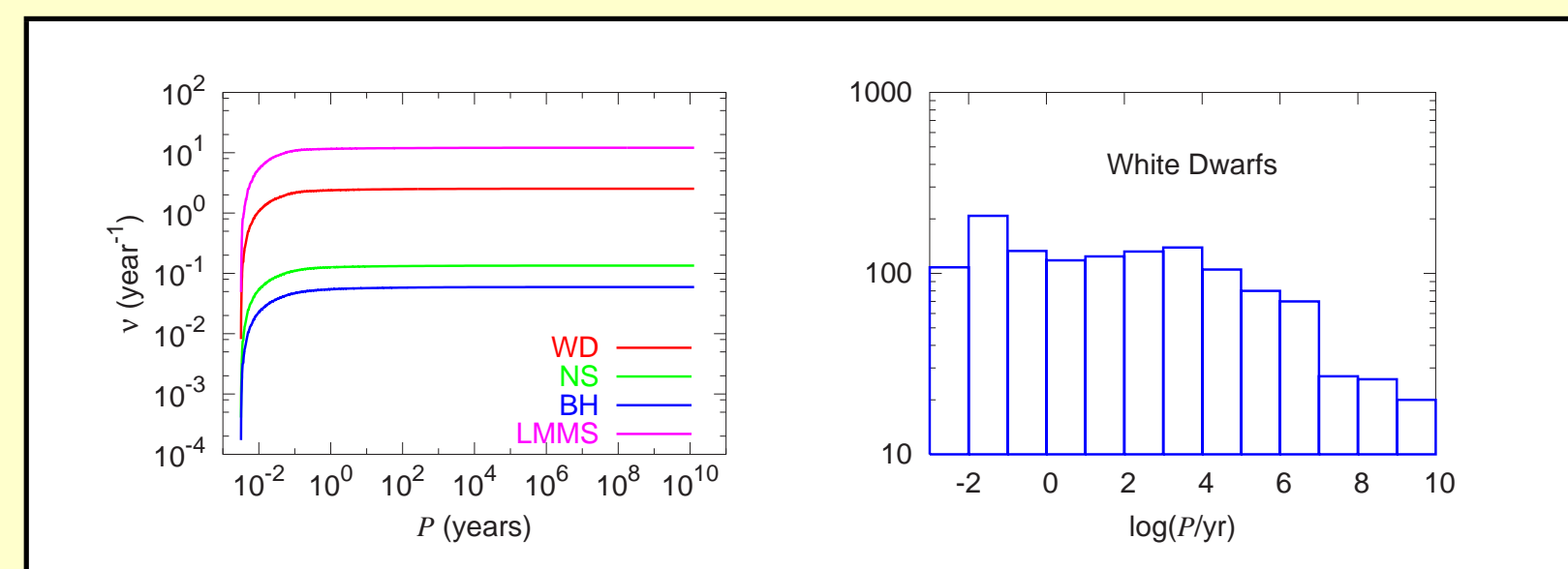

Milky Way Event Rates

The total event rate, ν, is the sum over all orbits with a SNR relative to LISA greater than five,

$$\nu = \sum_{SNR>5} \left(\frac{N_{\mathrm{LMMS,survive}}}{P_{\mathrm{orb}}} + \frac{N_{\mathrm{WD}}}{P_{\mathrm{orb}}} + \frac{N_{\mathrm{NS}}}{P_{\mathrm{orb}}} + \frac{N_{\mathrm{BH}}}{P_{\mathrm{orb}}} \right).$$

For our Milky Way bulge model, we find individual event rates of $\nu_{\mathrm{WD}} = 3$ yr^{-1}, $\nu_{\mathrm{NS}} = 0.1$ yr^{-1}, $\nu_{\mathrm{BH}} = 0.06$ yr^{-1}, and $\nu_{\mathrm{LMMS,survive}} = 12$ yr^{-1}. These event rates are large enough to consider EMRBs as a new class of gravitational waves sources in the LISA band.

In the figure below the left panel shows the accumulative event rate as a function of orbital period. Most EMRBs originate from orbits that would produce multiple bursts of radiation in a single mission lifetime ($\sim$3 years) and are on the verge of becoming EMRIs. However, a small fraction of the event rate is attributed to orbits with very large orbital periods as evident from the right figure, which shows the number of detectable white dwarf orbits as a function of the orbital period.

Virgo Event Rates

The next figure shows the number of black hole EMRBs as a function of SNR. The red region are undetectable systems, the green are detectable within the Milky Way, and the blue are observable out to Virgo.

If we repeat our analysis with the EMRB distances set to 16 Mpc and multiply by the number of galaxies in the cluster, we find a Virgo event rate of $\sim$3 yr^{-1}, all due to encounters of low mass black holes with central MBHs.

Paper Reference

L. J. Rubbo, K. Holley-Bockelmann, and L. S. Finn, arXiv/astro-ph/0602445 (2006), Submitted to ApJL
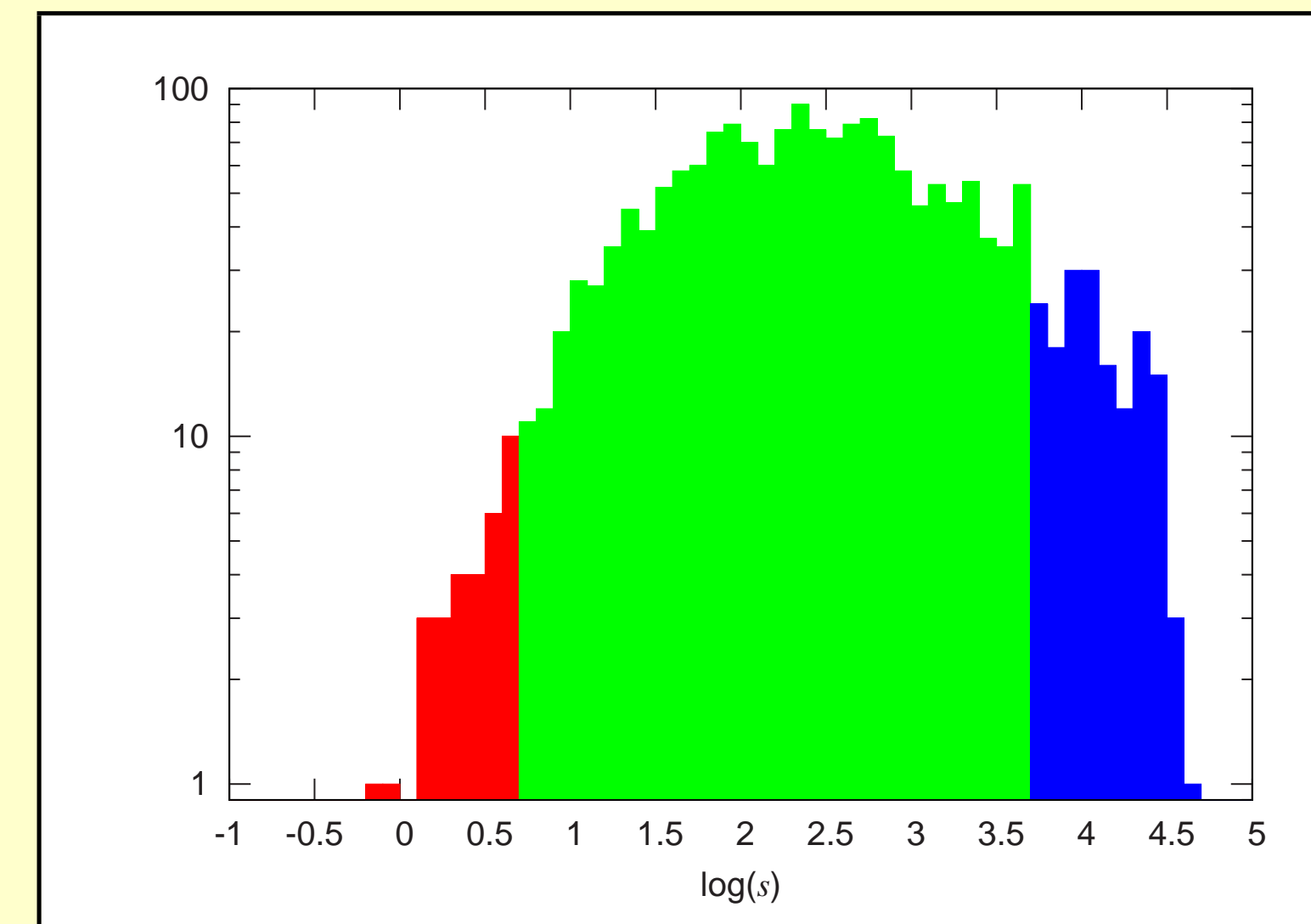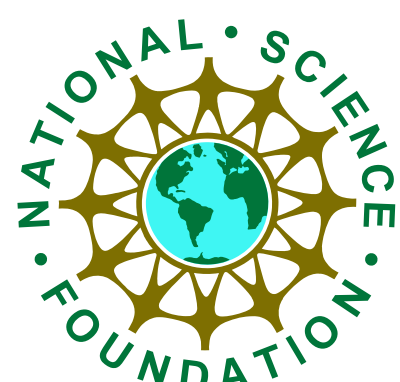
Future Considerations

Since we were primarily concerned with determining whether EMRBs are an overlooked class of LISA sources, we considered the simplest possible model, both for the Milky Way bulge and the estimate of the signal strength. Therefore, the real EMRB rate in the Milky Way is still slightly uncertain. To better characterize EMRBs and to study how they can constrain astrophysical models, future work must include more accurate models for the gravitational wave emission, including a better treatment of the orbit in the relativistic regime, and more realistic, time-dependent galaxy models, including a proper treatment of stellar dynamics such as mass segregation.

Additionally, we have introduced EMRBs as the evolutionary precursor to EMRIs. This implies, though, that the lifespan of an object in the EMRB phase may only be $\mathcal{O}(10^7) - \mathcal{O}(10^9)$ years after galaxy formation or a star formation episode. In order for there to be a significant population of detectable EMRBs in the present-day galaxy sample, there must be a refilling mechanism responsible for keeping the EMRB region of phase space occupied. There are several possible refilling mechanisms, such as triaxiality or substructure accretion, which may ensure that this region is supplied with compact objects. Future research will need to focus on the importance of such contributions.